Assessing Long-Term Physical Stability and Benthic Infaunal Colonization of a Sediment Cap Placed over Chemically Contaminated Bottom Sediments in the Wyckoff/Eagle Harbor Superfund Site, Bainbridge Island, Washington

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Introduction

A sediment cap was placed over chemically contaminated sediments in Eagle Harbor, Washington as part of a cleanup action at the Wyckoff/Eagle Harbor Superfund Site (U.S. EPA et al., 1994). The Wyckoff/Eagle Harbor Superfund Site is located on the eastern side of Bainbridge Island, Washington, approximately six nautical miles west of Seattle (Figure 1). The site was added to the U.S. EPA National Priorities List of Superfund Sites in 1987. Several studies, including a remedial investigation and feasibility study (RI/FS) conducted by the EPA identified elevated levels of polycyclic aromatic hydrocarbons (PAHs) and mercury in marine sediments in the East Harbor (CH_2M Hill, 1989, 1991a, 1991b). Total PAH concentrations in East Harbor sediments ranged from greater than 10,000 parts per billion (µg/kg) to as high as 30,000,000 µg/kg at the “hot spot” (Tetra Tech, 1986). The principal source for the PAHs is a now inactive wood-treatment facility located on the south side of the harbor which treated wood pilings with creosote to prevent biological fouling and shipworm decay. The wood-treatment facility began operations in 1903 and was still in operation as late as 1988. Mercury is believed to have entered the harbor from ship sand-blasting and maintenance by former shipyards located on the northwest shore of Eagle Harbor. Mercury levels in the East and West Harbor sediments exceed the Washington State Sediment Management Standards Minimum Cleanup Levels (Washington Administrative Code [WAC] 173-204-520; Ecology, 1996).

Removal Action

On June 15, 1993, EPA issued an Action Memorandum initiating the first phase of cleanup of the East Harbor Operable Unit (OU) under CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act). The first cleanup phase under the Removal Action consisted of capping the contaminated sediments in the East Harbor where biological effects had been documented (CH2M Hill, 1989). The sediment cap was constructed to physically isolate the contaminated sediments from the marine environment, to prevent heavily contaminated areas from acting as a source of contamination to other areas of Eagle Harbor, to provide clean habitat for sediment-dwelling organisms, and to bring surface sediments in the East Harbor into compliance with the Washington State Sediment Management Standards Minimum Cleanup Levels (Ecology, 1996).

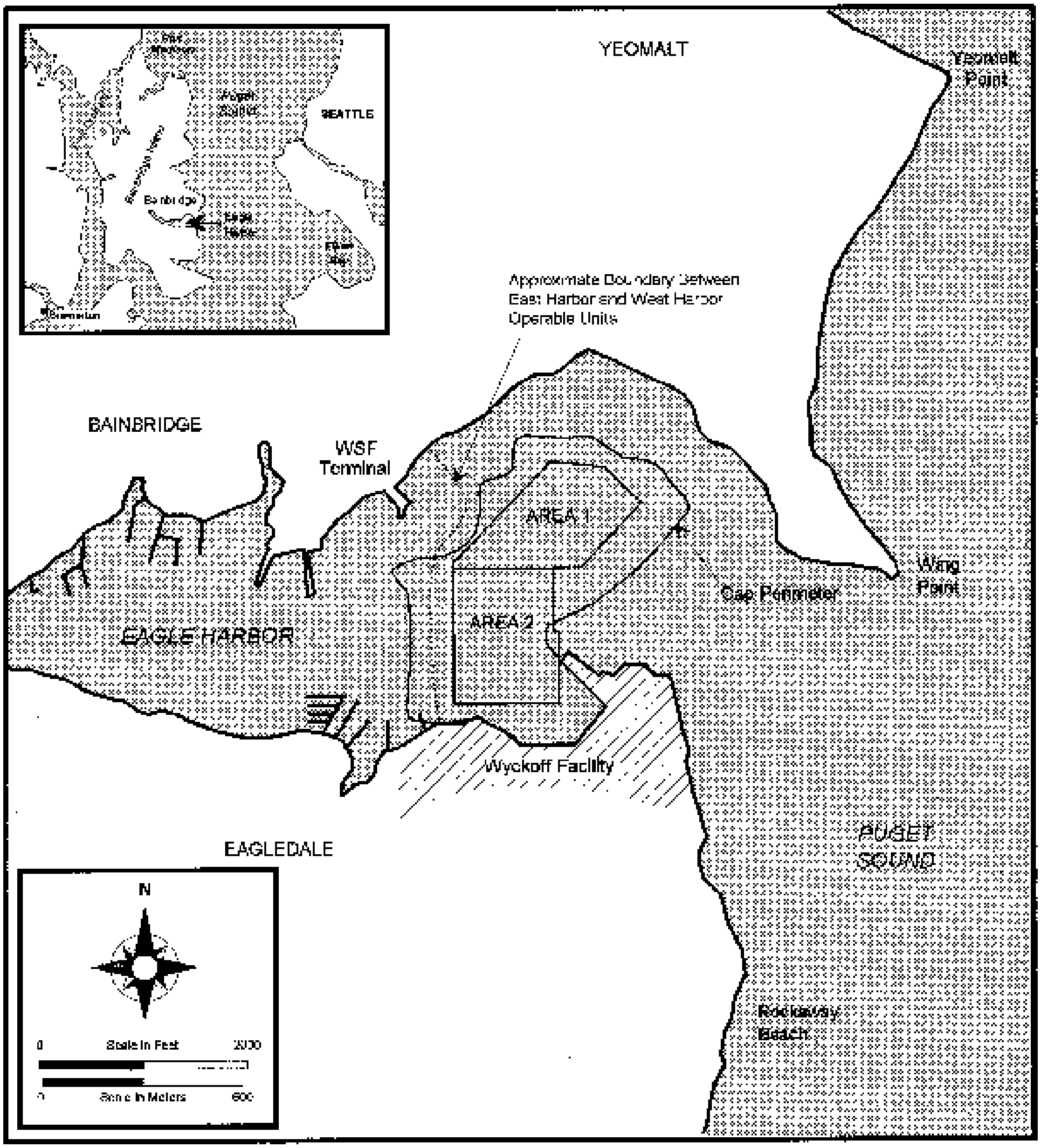

Figure 1. Wyckoff/Eagle Harbor Superfund site, East Harbor operable unit.

The design, construction, and long-term monitoring of the East Harbor sediment cap was conducted by the U.S. Army Corps of Engineers, Seattle District for the EPA, Region 10. The cap was constructed between September 1993 and March 1994. Approximately 136,900 cubic yards (211,000 cubic meters) of clean sandy sediment dredged from the Snohomish River federal navigation channel were placed over 54 acres (21.4 hectares) of chemically contaminated bottom sediment. Cap material placement was conducted by split-hull barge in the more consolidated northern areas of the East Harbor (Area 1), and by hydraulic wash-off from a flat-deck barge in the less consolidated southern areas (Area 2). Final thickness of the sediment cap ranged from one to six feet (0.3 to two meters). A contoured thickness map based on a post-cap placement sub-bottom sonar survey is presented in Figure 2.

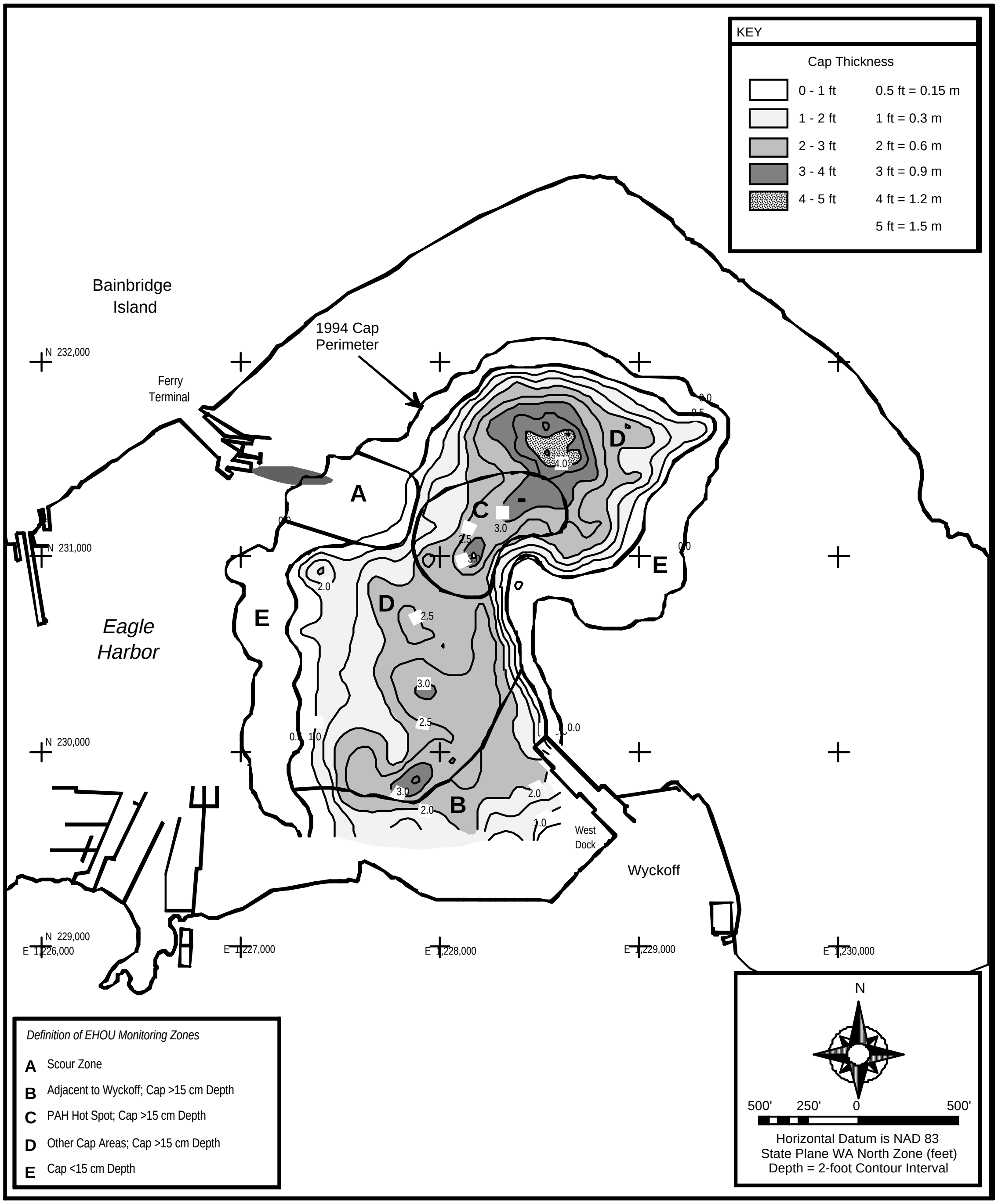

Figure 2. Contour of cap thickness determined by the post-placement sub-bottom sonar survey. Cap monitoring zones are also displayed.

Long-Term Monitoring

Long-term monitoring of the sediment cap is required to ensure that the cap is physically stable and remaining in place at the desired thickness, and to determine whether the cap sediments are providing suitable habitat for bottom-dwelling (benthic) organisms. Monitoring of surface sediment cap chemistry to ensure compliance with the Washington State Sediment Management Standards and monitoring of sub-surface sediment chemistry to assess whether upward migration of contaminants are occurring are also important objectives in the long-term monitoring of the cap, but are not addressed in this paper.

Readers interested in sediment chemistry results for the long-term monitoring program are encouraged to contact the EPA Region 10, in Seattle, Washington.

During the design process of the sediment cap, it was acknowledged that portions of the cap could be affected by erosion, based on modeling presented in the Remedial Investigation (CH_2M Hill, 1989). The main source of erosive energy is the propeller wash from commuter ferries. The Washington State Department of Transportation ferry terminal for the Bainbridge Island-to-Seattle route is located on the north shore of Eagle Harbor. Long-term physical stability results will be used to refine the limits of the erosive areas and cap armoring will be designed, if necessary.

Following completion of the East Harbor OU sediment cap, monitoring zones were defined for the different areas of the cap, based on the existing physical and chemical environments (Figure 2). Monitoring zones were defined for the following cap conditions:

Zone A: This scour area is near the ferry terminal, where cap erosion is most likely due to ferry propeller wash.

Zone B: This depositional area is adjacent to the Wyckoff property and has the potential for surface re-contamination. Cap thickness ranges from 0.5 ft (15 cm) to more than 2.5 ft (>75 cm).

Zone C: Cap area where underlying sediments are highly contaminated ("hot spot"). There is potential for scouring based on its proximity to Zone A. Cap thickness in this zone is generally greater than 2 ft (> 60 cm).

Zone D: Cap areas not adjacent to contaminant sources or erosional forces. Cap thickness ranges from 0.5 ft (15 cm) to greater than 4 ft (> 120 cm) in some areas.

Zone E: Periphery of the sediment cap where cap thickness is 0.5 ft or less (≤ 15 cm).

Methods

The principal tools for assessing cap physical stability are the sequential measurement of cap thickness using precision bathymetric surveys (acoustic seafloor mapping) and REMOTS® (Remote Ecological Monitoring of the Seafloor) sediment profile photography. Determining whether cap sediments are providing suitable habitat for benthic infauna is also assessed using REMOTS® photography.

Precision Bathymetric Surveys

Precision bathymetric surveys (acoustic seafloor mapping) were conducted in the East Harbor using an Odom DF3200 Echotrac® fathometer with a narrow-beam 208-kHz transducer integrated with a portable navigation and survey system for automated data acquisition. Navigation was provided by a differential global positioning system (DGPS) with a positional accuracy of ±2 meters in real time. Depth soundings and position data were recorded at one-second intervals. Depth data were corrected for speed-of-sound in seawater, vessel draft (depth of the transducer below the water surface), and tides. Speed-of-sound corrections were measured using a Sea-Bird SeaCat CTD profiler and tidal corrections to Mean Lower Low Water (MLLW) were obtained from the Seattle, Washington NOAA tide station.

Following completion of each bathymetric survey, the survey data was edited, filtered, and correction factors were applied. Individual survey lanes were edited and outliers (e.g., bubbles from ferry propeller wash) were deleted from the database. To compare bathymetric surveys and assess cap stability, the depth data points for each survey were gridded into an array (matrix) of equally spaced cells. One depth value was calculated for each cell using a weighted average interpolation algorithm. By comparing survey grids between years, areas where changes in cap thickness have occurred can be identified. Survey data processing and gridding were conducted using processing software developed by SAIC, and Surfer®

version 6.0. Depth difference comparisons between bathymetric surveys can show changes in cap thickness that are greater than or equal to 1 foot (≥ 60 cm).

REMOTS® Sediment Profile Photography

REMOTS® is a standardized method developed for sediment profile image collection, analysis, and interpretation (Rhoads and Germano, 1982; 1986). The REMOTS® camera can obtain in-situ profile images of up to 20 centimeters (cm) of the upper sediment column. Profile images collected in Eagle Harbor were used to locate the perimeter of the sediment cap and measure cap thickness in thinly capped areas (Zone E). Sediment profile photography is used by the Dredged Material Management Program (DMMP) to conduct environmental monitoring and mapping of dredged material disposal sites in Puget Sound (SAIC, 1992; 1994; 1996). In addition to cap material mapping, several biological parameters were measured from the REMOTS® images to provide an indication of sediment habitat quality.

Sediment profile photographic images are collected using a Benthos model 3731 sediment-profile camera (Benthos, Inc., North Falmouth, MA) (Figure 3). The sediment-profile camera consists of a wedge-shaped prism with a Plexiglas face plate and a back mirror mounted at a 45° angle. Light is provided by an internal strobe. The mirror reflects the image of the profile of the sediment-water interface up to a 35-mm camera that is mounted horizontally on top of the prism.

The camera prism is mounted on an assembly that can be moved up and down within a stainless steel frame by allowing tension or slack on the winch wire. The rate of fall of the prism (6 cm/second) is controlled by an adjustable passive hydraulic piston, which minimizes the disturbance of the sediment-water interface. A trigger is tripped on impact with the bottom, activating a 13-second time delay on the shutter release; this allows maximum penetration of the prism before a photograph is taken. When the camera is raised from the bottom, a wiper blade automatically cleans off any sediment adhering to the prism faceplate, the film is advanced, and the strobes are recharged. A Benthos Model 2216 pinger is coupled to the camera frame so that the camera can be acoustically tracked to the bottom. The ping rate doubles for a period of 10 seconds after each photograph is taken, verifying image acquisition.

Physical and biological parameters are measured directly from the REMOTS® transparencies using a video digitizer and computer image analysis system. The image analysis system can discriminate up to 256 different tonal color scales, so subtle features can be accurately digitized and measured. The image analysis software allows the measurement and storage of data from up to 21 different variables for each image. The specific REMOTS® parameters used for the long-term monitoring of the East Harbor sediment cap include cap material distribution, sediment grain size major mode, surface boundary roughness, apparent Redox Potential Discontinuity (RPD) depth, infaunal successional stage, and calculation of the organism-sediment index (OSI).

Cap Material Distribution

Measuring the distribution and thickness of the East Harbor sediment cap in sediment profile images depends on optical differences in sedimentary characteristics of the cap material compared to the ambient seafloor. Recently deposited dredged material at a disposal site (or capping site) will typically have unique textural and fabric properties relative to ambient sediments. The dredged material may have a reduced, poorly sorted and chaotic sedimentary fabric if deposited rapidly, or it may show sorted grain-size layers due to discreet depositional events. The dredged material can be clearly distinguished when compared to homogeneous, oxidized, olive-colored surface sediments typical of undisturbed ambient conditions. Because the sediment profile camera is limited to the upper 15 to 20 cm of the sediment column, actual cap thickness measurements using the REMOTS® camera were made only where ambient sediments were visible (thinly capped areas). REMOTS® photography was effective in mapping the perimeter of the sediment cap.

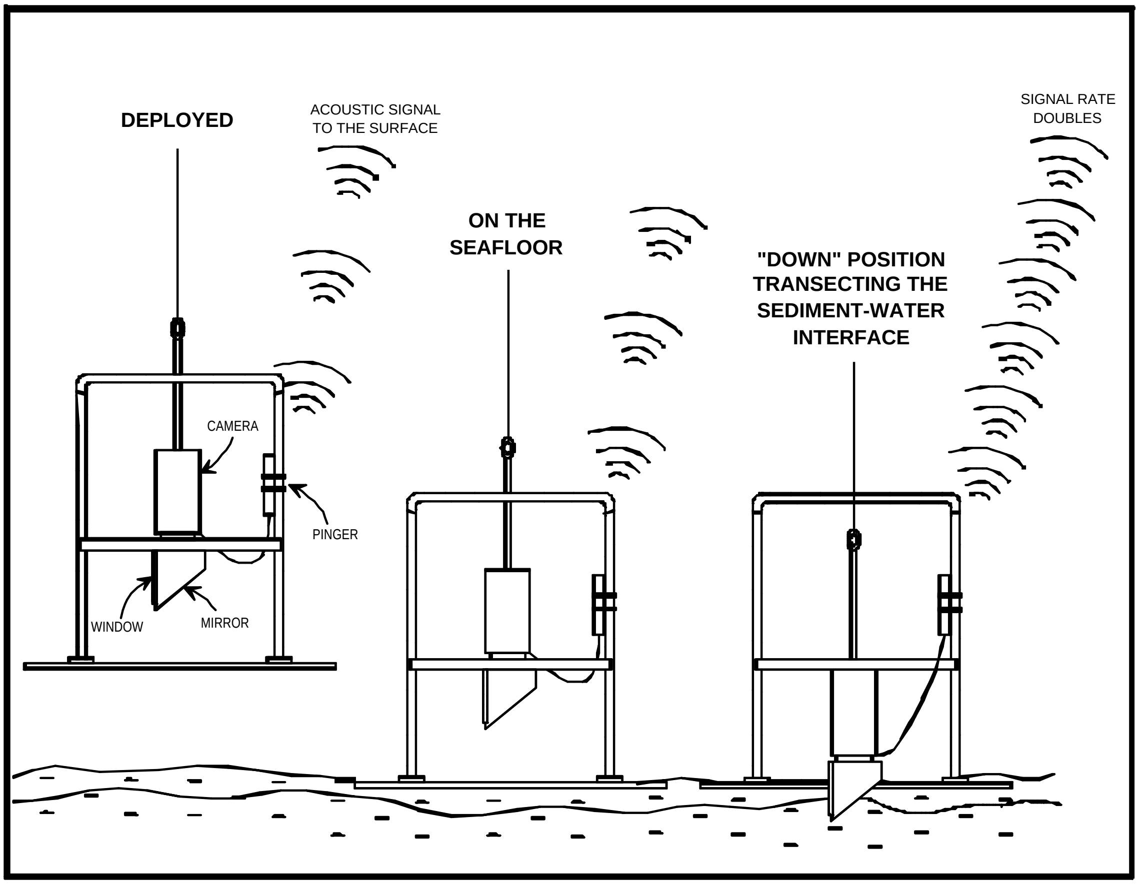

Figure 3. Diagram of the Benthos Model 3731 sediment-profile camera in operational mode.

Sediment Grain-Size

The sediment grain-size major mode and range, in phi units, were visually determined from the sediment profile images by overlaying a grain-size comparator at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) through the REMOTS® optical system. Seven grain-size classes are on this comparator: ≥ 4 phi (≤ 0.0156 mm; silt/clay), 4-3 phi (0.0625 - 0.125 mm; very fine sand), 3-2 phi (0.125 - 0.25 mm; fine sand), 2-1 phi (0.25 - 0.50 mm; medium sand), 1-0 phi (0.50 - 1.00 mm; coarse sand), 0-(-1) phi (1.00 - 2.00 mm; very coarse sand), and <-1 phi (> 2.00 mm; gravels). The lower limit of optical resolution is about 62 µm, allowing recognition of grain sizes equal or greater than coarse silt. The accuracy of this method has been documented by comparing REMOTS® estimates with grain-size statistics determined from laboratory sieve analyses (SAIC, 1986).

Surface Boundary Roughness

Surface boundary roughness was determined by measuring the vertical distance (parallel to the film border) between the highest and lowest points of the sediment-water interface. In addition, the origin (physical or biogenic) of this small-scale topographic relief is recorded. In sandy sediments, boundary roughness can be a measure of sand-wave height. On silt-clay bottoms, boundary roughness values often reflect biogenic features such as fecal mounds or surface burrows. These features are abundant only in areas where boundary shear stresses are low enough that such delicate features are preserved. Disposed dredged material often introduces high surface relief on an otherwise "smooth" bottom. Other surface features are noted when evident, including shell fragments/lag deposits, mud-clay clasts, and wood debris.

Apparent Redox Potential Discontinuity (RPD) Depth

The upper surface of aerobic fine-grained sediments has a higher light reflectance value relative to underlying hypoxic or anoxic sediments. This is readily apparent in REMOTS® images and is due to oxidized surface sediment that contains minerals in an oxidized state (typically an olive brown color), while the reduced sediments below this oxygenated layer are generally gray to black. The boundary between the colored ferric hydroxide surface sediment and underlying sediment is called the apparent redox potential discontinuity (RPD).

The actual RPD is the boundary that separates the positive Eh region (presence of free oxygen) of the sediment column from the underlying negative Eh region (absence of free oxygen). The exact location of the Eh boundary (where Eh=0) can only be determined with microelectrodes. Therefore, the reflectance boundary observed in the REMOTS® images is termed the apparent RPD. In general, the depth of the actual RPD will be shallower than the depth of the apparent RPD, because bioturbating organisms mix ferric hydroxide-coated particles downward below the Eh=0 horizon. As a result, the apparent RPD depth provides an estimate of the degree of biogenic sediment mixing. This variable is important in evaluating the effect of colonizing benthos on disposed sediments. Bioturbation vertically transports buried reduced compounds to the sediment surface and exposes them to an oxidizing water column (Aller, 1982). Bioturbation also affects sediment transport by changing the physical properties of sediments and their mechanical behavior (Rhoads and Boyer, 1982).

Infaunal Successional Stage

The mapping of infaunal successional stages from sediment profile images is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor disturbance. This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediments in specific ways. Because functional types are the biological units of interest, our definition does not demand a sequential appearance of particular invertebrate species or genera" (Rhoads and Boyer, 1982). This theory is formally developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982) and is based on a large body of observations from water depths of less than 30 meters.

In shallow water environments, infaunal succession following a major seafloor disturbance initially involves pioneering populations (Primary or Stage I succession) of very small organisms that live at, or near, the sediment-water interface (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986). In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated as Stage II. Large, deep-burrowing infauna, or Stage III taxa, represent a high-order successional stage typically found in areas of low disturbance.

Many deep-burrowing infauna feed at depth in a head-down orientation. The localized feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include a generally semicircular shape with a flat bottom and arched roof, and a distinct granular change in the sediment particles overlying the floor of the structure. The relatively coarse-grained material represents particles rejected by the head-down deposit-feeder, as these deep-dwelling infauna preferentially ingest the finer sediment particles. Other subsurface structures, including burrows or methane bubbles, do not exhibit these characteristics. The bioturbation activities of these deposit-feeders are responsible for aerating the sediment and causing the apparent RPD depth to be located several centimeters below the sediment-water interface.

Organism-Sediment Index

The Organism-Sediment Index (OSI) provides a measure of general benthic habitat quality in shallow water environments based on dissolved oxygen conditions, depth of the apparent RPD, infaunal successional stage, and presence or absence of sedimentary methane (Rhoads and Germano, 1986). The OSI is a numerical index ranging from -10 to +11. The lowest value is given to bottom sediments with low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment. High OSI values are given to aerobic bottom sediments with a deep apparent RPD, mature macrofaunal community, and no methane gas. Parameters for the OSI are measured visually from the REMOTS® images. The numerical values and ranges used in calculating the OSI are provided in Table 1.

Table 1. Calculation of the Organism-Sediment Index.

Choose One Value:		
	Mean RPD Depth Classes	Index Value
	0.00 cm	0
	> 0–0.75 cm	1
	0.76–1.50 cm	2
	1.51–2.25 cm	3
	2.26–3.00 cm	4
	3.01–3.75 cm	5
	> 3.75 cm	6
Choose One Value:		
	Successional Stage	Index Value
	Azoic	– 4
	Stage I	1
	Stage I–II	2
	Stage II	3
	Stage II–III	4
	Stage III	5
	Stage I on III	5
	Stage II on III	5
Choose One or Both if Appropriate:		
	Chemical Parameters	Index Value
	Methane Present	– 2
	No/Low Dissolved Oxygen	– 4
Organism-Sediment Index =		Range: –10 + 11

Results

Following completion of the East Harbor sediment cap in March 1994, a post-placement bathymetric survey and REMOTS® survey were conducted to document conditions of the completed cap. Results from these surveys provide a baseline comparator for assessing the long-term physical stability of the cap. In addition, biological parameters measured during the post-placement REMOTS® survey provide a benchmark from which benthic colonization of the sediment cap can be measured.

Two monitoring events have been conducted as part of the long-term monitoring of the East Harbor sediment cap. Monitoring one year after completion of the cap occurred in the fall of 1995; monitoring three years after completion of the cap occurred in the summer of 1997. Bathymetric surveys and REMOTS® photography surveys were conducted in both monitoring years. However, the 1995 bathymetric survey was conducted by the National Oceanic and Atmospheric Administration (NOAA) as part of the navigational charting program. Data densities for the NOAA survey and the 1994 post-placement bathymetric survey were found to be incompatible, so a comparison between the surveys could not be made. All other monitoring data (bathymetry and REMOTS®) could be compared to the post-placement survey data to assess physical stability of the cap.

Physical Stability of the East Harbor Cap

REMOTS® survey results indicate a slight eastward shift of the northeastern perimeter of the cap, but significant changes in the overall distribution of cap material has not occurred since cap placement (Figure 4). Cap material was identified in REMOTS® images by its optical contrast to native sediments. Cap sediments are composed primarily of tan to gray, poorly sorted sands with woody debris, and native sediments are generally composed of tan, well-sorted sands or silts. Cap material visible in 1995 along the eastern cap perimeter is absent in 1997. The apparent loss of cap material is likely due to biological mixing of sediments. Over time, the optical distinction between cap material and native sediments will be obscured by sediment bioturbation.

Results of the 1997 bathymetric survey were compared with those of the 1994 post-placement survey to determine whether changes have occurred in areas where cap thickness was greater than one foot (>30 cm). Cross-sections of the 1997 survey were made in areas most likely to show evidence of changes in cap thickness and compared to the same cross-sections from the 1994 post-placement survey (Figure 5). With the exception of Zone A, cross-section comparisons of the bathymetric data suggest that cap thickness has not changed significantly.

Cross-section A-A' (Figure 6) begins at the ferry terminal and runs due east toward the outer harbor. The cross-section data shows that approximately 40 cm (1.3 ft) of material has been lost in the scour zone since placement of the cap. Loss of cap material was also evident in this area during the 1995 REMOTS ® survey. Along the eastern portion of the transect, where the harbor bottom transitions to the outer harbor, the 1997 survey shows approximately 22 cm (0.7 ft) of material accumulation. Cross-section B-B' (Figure 7) is oriented north-south across the eastern portion of the cap. The cross-section data show no significant difference between the two surveys. The apparent accumulation of material along the northern part of the cross-section is less than 15 cm (<0.5 ft). Cross-section C-C' (Figure 8) begins in the southwest corner of the cap and crosses northeast to the edge of the cap. The cross-section data show no significant changes in the southern portion of the cap. The northern portion of the cap also appears unchanged, with the exception of the cap material mounds. During cap construction, mounds of cap material were created in the northern portion of the cap when portions of the cap material load would "hang up" in the split-hull barge and then rapidly exit in a clump (U.S. EPA et al., 1994). A cap material mound visible in cross-section C-C' shows evidence of smoothing since cap placement.

Depth differences of ±1 ft (±30 cm) or more measured between the 1994 and 1997 surveys are contoured and plotted in Figure 9. Cap sediments have been eroded in some areas of Zone A, but have also been re-deposited within Zone A. In the eastern portion of the cap, Zone E and parts of Zone D appear to show some areas (diameter of 50 to 100 ft [15 to 30 m]) with cap material loss up to 2 ft (60 cm). This represents approximately 2200 m^3 of material, or 1.0 % of the total volume of cap material (211,000 m^3) placed in Eagle Harbor. However, the apparent loss of cap material in Zone E is not corroborated by the REMOTS® data. Sediment accumulation mounds recorded in the southern portion of the cap are bathymetric survey artifacts; barges and vessels anchored in the southern cap area during the 1997 bathymetric survey prevented the survey vessel from reaching those areas.

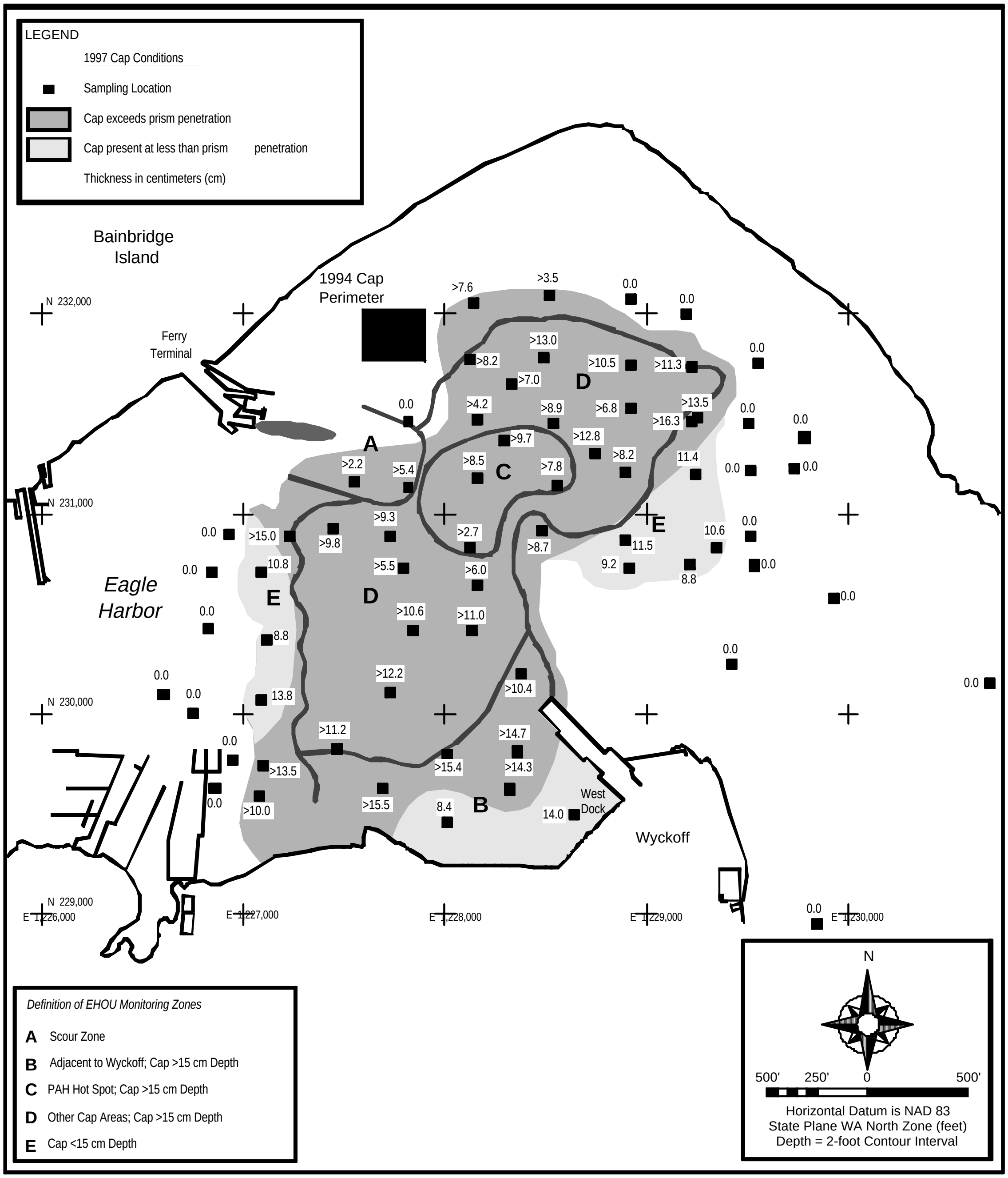

Figure 4. Cap material distribution on REMOSAE surveys conducted of the East Harbor cap.

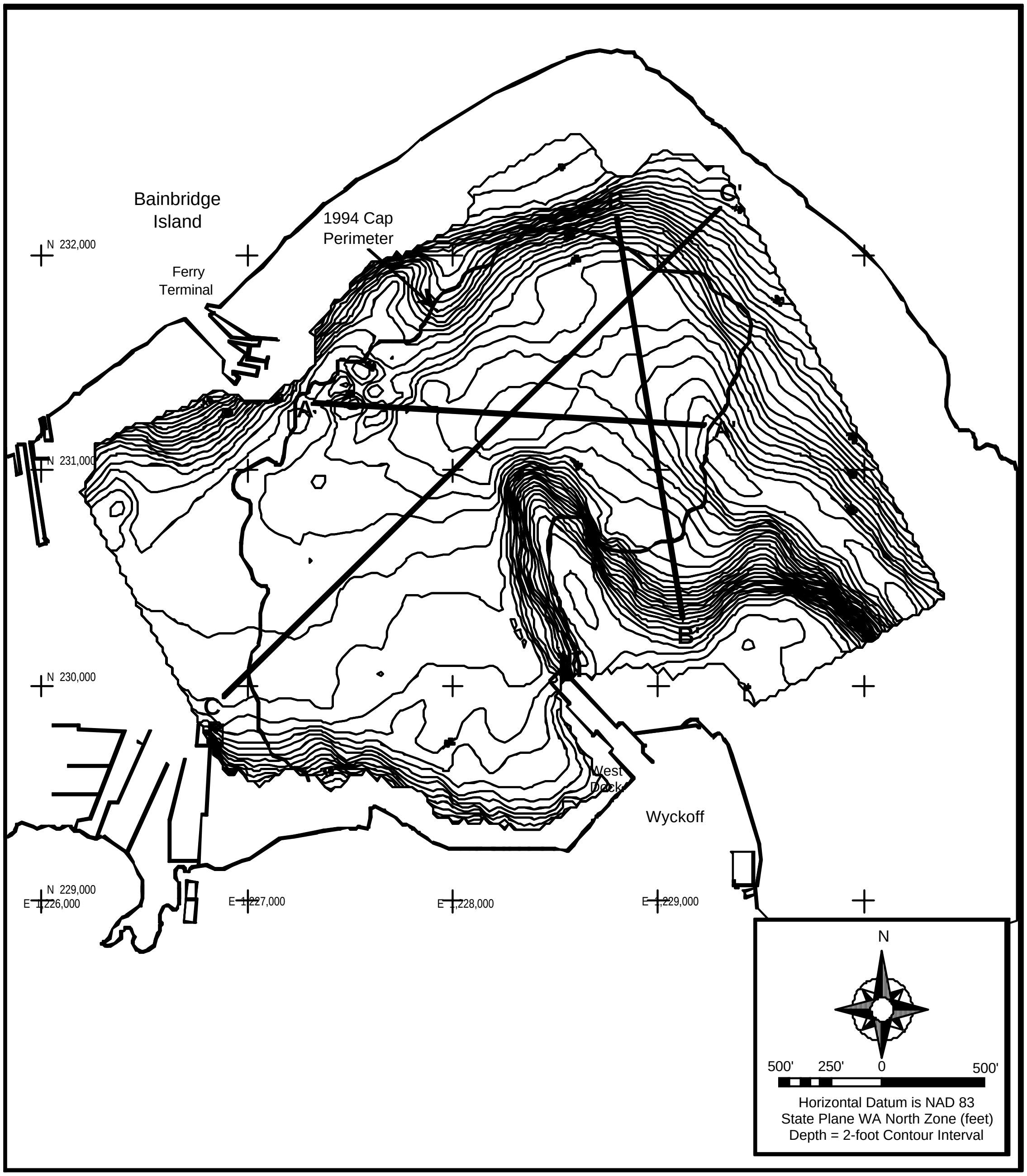

Figure 5. Eagle Harbor 1997 bathymetry survey and cross sections for comparison to the 1994 post-placement survey.

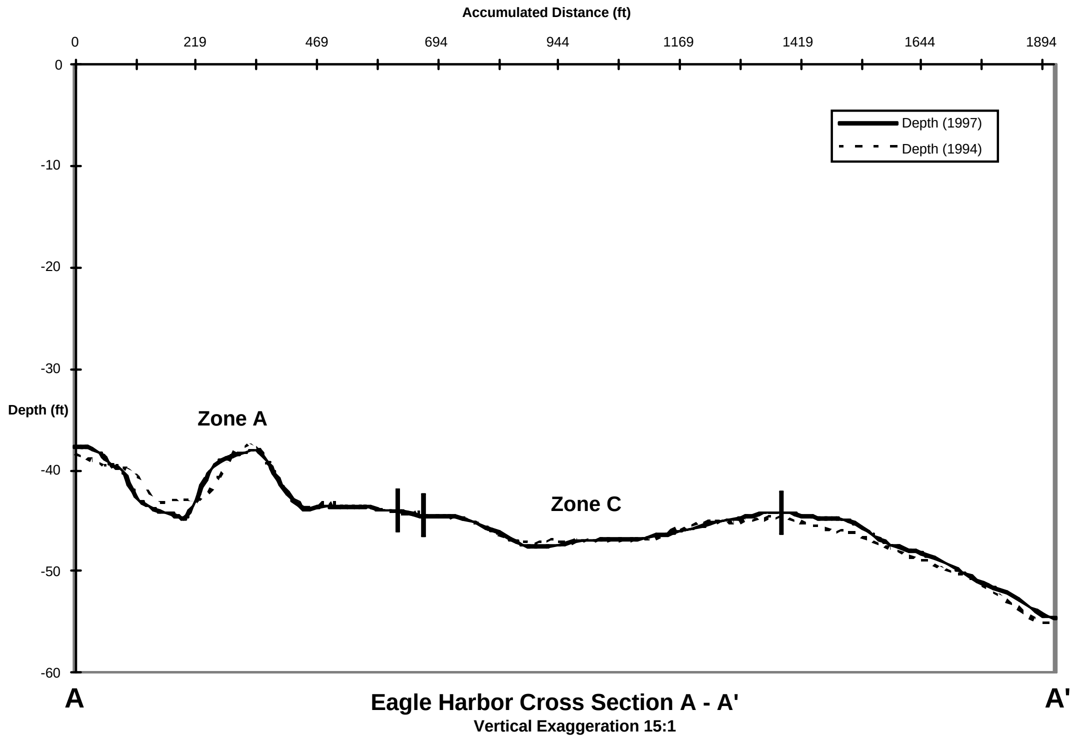

Figure 6. Cross section A-A'. 1994 and 1997 bathymetric data.

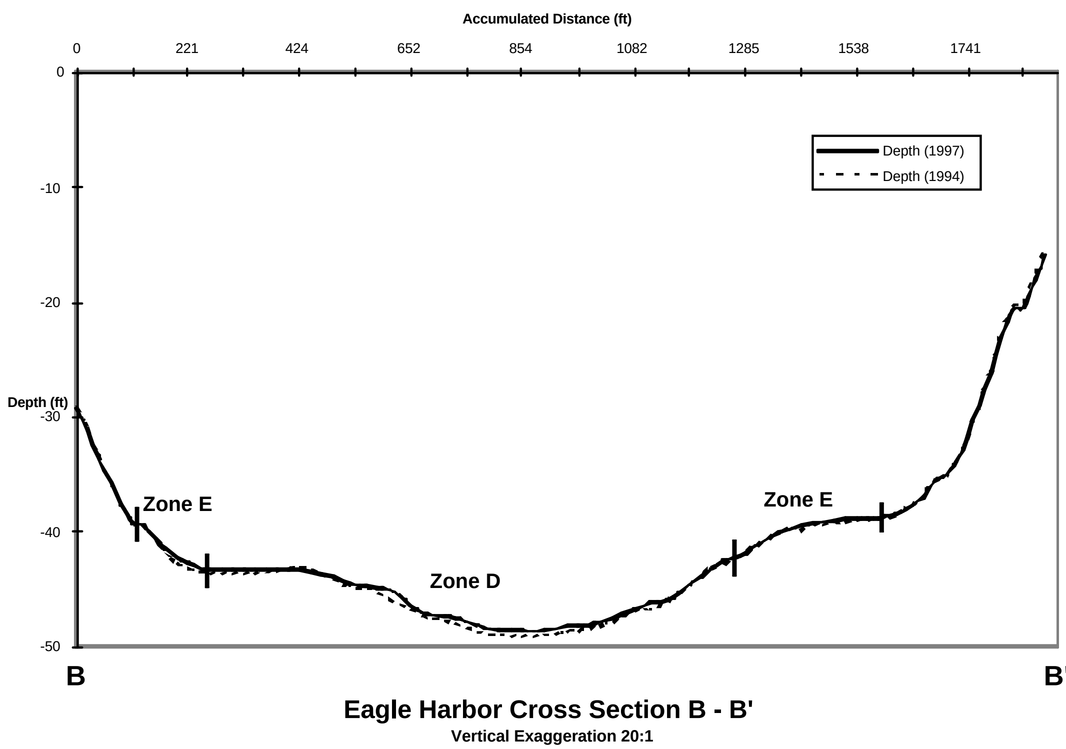

Figure 7. Cross section B-B'. 1994 and 1997 bathymetric data.

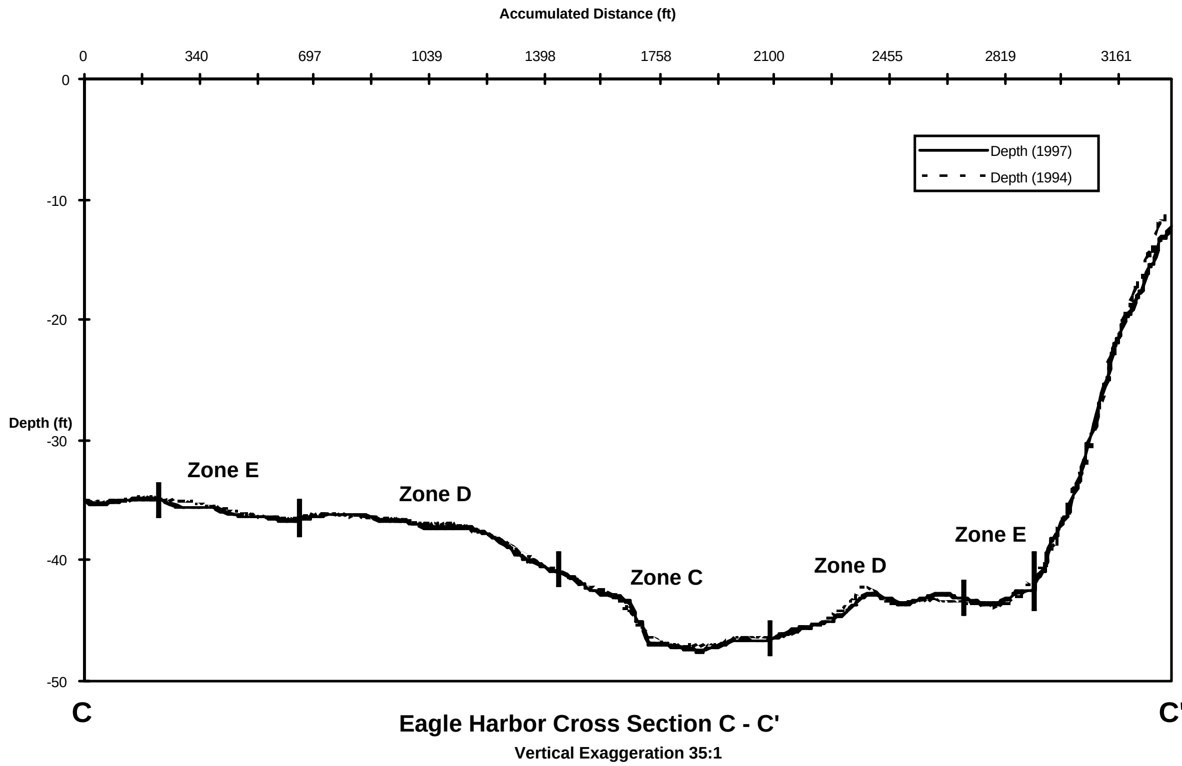

Figure 8. Cross section C-C'. 1994 and 1997 bathymetric data.

Benthic Colonization of the Cap

REMOTS® images were analyzed for the RPD depth, infaunal successional stage (the functional type of infaunal organisms present), the presence of methane, and the presence of oxic or anoxic sediments to assess benthic infaunal colonization. These parameters are used to calculate OSI values, which provide a general indicator of cap sediment habitat quality for the colonizing benthic infauna.

Mean RPD depths have increased over time in most areas of the East Harbor OU cap, suggesting increased levels of sediment bioturbation by the benthic infauna. During the post-placement survey in 1994, the mean for all RPD depths was 2.49 cm. In 1997, the mean for all RPD depths had increased to 3.28 cm. Infaunal successional stages present on the cap are also transitioning to Stage III communities. In 1997, Stage III infauna (long-lived successional stages) were observed in the northern and southern portions of the cap, and at two stations in the central cap region. The frequency of Stage III classifications has increased since cap placement, from 25% of all stations during the 1995 survey to 38% during the 1997 survey. OSI values for the East Harbor sediment cap have thus improved since cap placement, suggesting that cap sediments are providing suitable habitat for benthic infauna (Figure 10). Following construction of the cap in 1994, the median OSI value was 5. The median OSI value was also 5 during the year-one survey in 1995, but had increased to 7 during the year-three survey.

Discussion

The distribution of the East Harbor sediment cap remains generally unchanged based on REMOTS ® measurements. However, small changes in the cap perimeter have been observed over time and can be attributed to variable redistribution of the cap material and bioturbation of the cap material with the ambient sediments. In the future, cap sediments at the margins of the cap will be well bioturbated with the native sediments, at which time sediment profile photography will no longer be able to visually distinguish thin capped areas (Zone E) from the ambient bottom sediments.

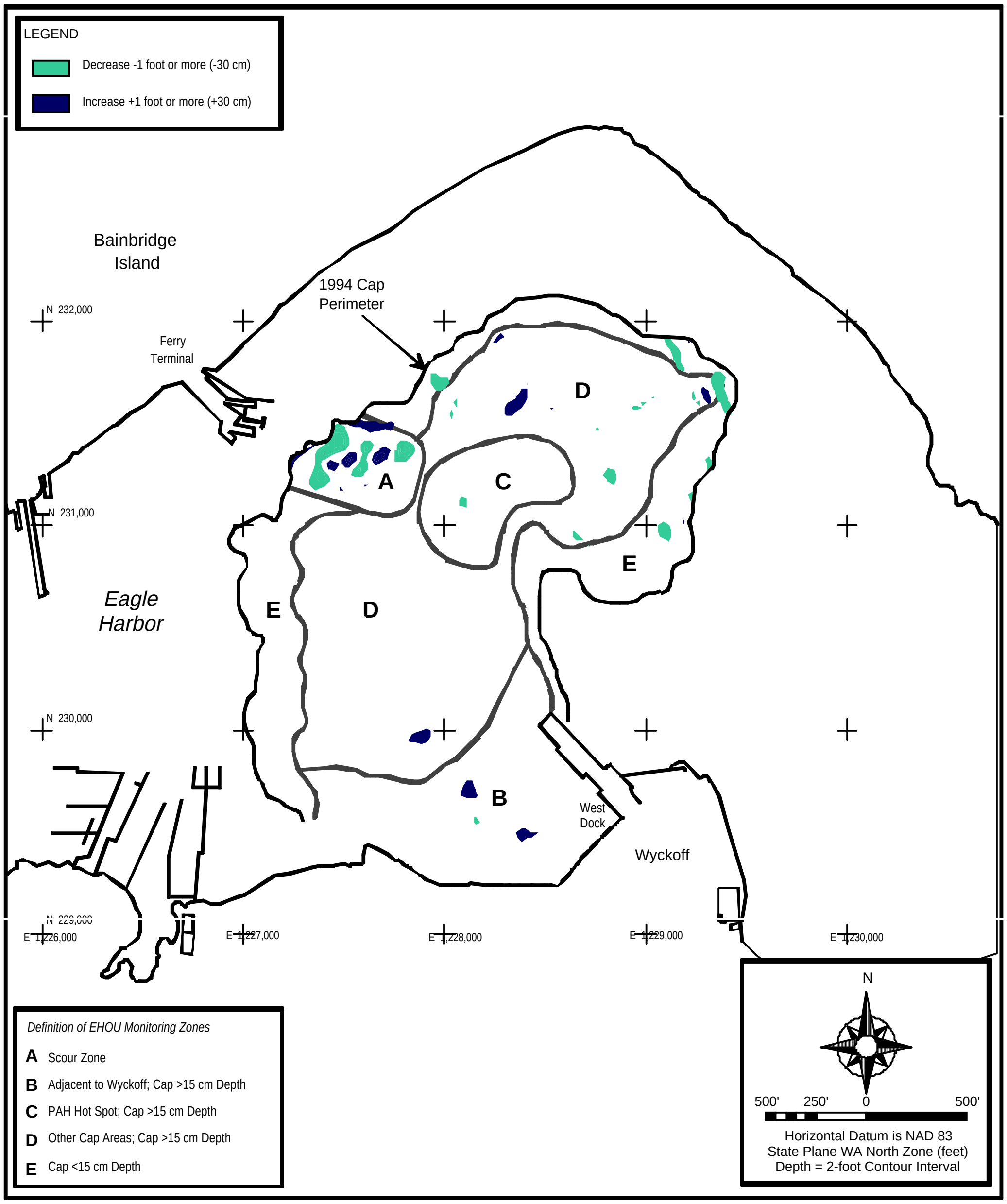

Figure 9. Depth differences greater than 1 ft (<30 cm) between 1994 and 1997 surveys.

Comparison of bathymetric surveys conducted in Eagle Harbor indicates very little change in the thickness of the cap (no greater than 1 foot), except in areas where erosion was anticipated (Zone A). However, the smoothing of cap material mounds in the northern portion of the cap suggests that some localized movement or settling of cap sediments has occurred since the cap was completed. REMOTS® images were examined for grain-size major mode, sediment sorting (armoring or winnowing of fine-grained sediment), and development of physical surface-boundary roughness features (ripples or bedforms) to locate potential areas of sediment instability or erosion. A REMOTS® image showing evidence of physical boundary roughness is presented in Figure 11.

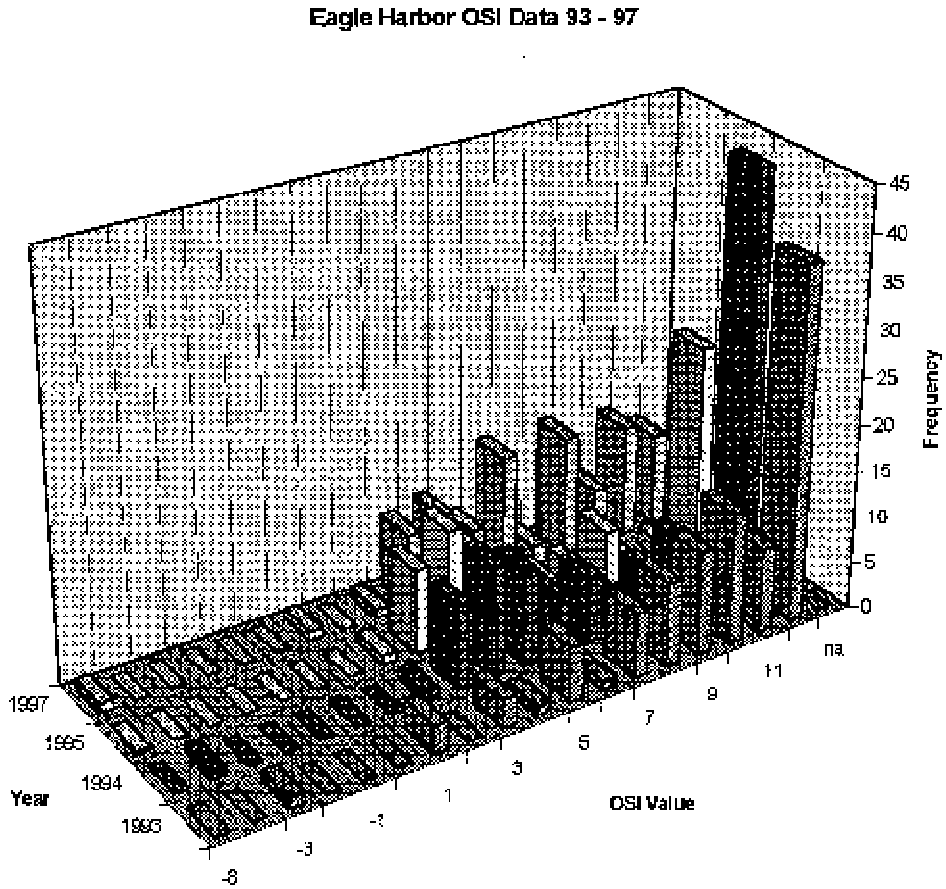

Figure 10. Frequency of Organism-Sediment Index (OSI) values measured at the East Harbor OU sediment cap.

Sediment grain-size measured in areas affected by ferry propeller wash reflect conditions where cap sediments have been winnowed of fine-grained material, or eroded away. Cap sediments are composed mostly of fine sands (4–3 phi). In much of Zone A and the surrounding regions of Zone C and D, medium sands (3–2 phi) are now present. Gravels (<–1 phi) are also present in Zone A, which clearly indicates erosion of cap material.

The area of the cap showing physically induced boundary roughness features due to ferry scour has increased over time. Areas showing physically induced boundary roughness features attributed to sediment resuspension or transport (ripples and sediment sorting) include Zone A (scour zone), the surrounding regions in Zones C and D, and parts of Zone E (Figure 12). Although the cap area showing physical boundary roughness has increased, the magnitude of physical boundary roughness has not changed significantly. In 1997, physical boundary roughness values ranged from a low of 0.27 cm at the northern portion of the cap to a high of 3.46 cm in the ferry scour zone (Zone A). The range of boundary roughness values is higher in comparison with previous surveys. However, the mean boundary roughness value for the 1997 survey (0.95 cm) was not significantly higher than that for the 1995 survey (0.82 cm).

Conclusions

Repetitive bathymetric surveys in conjunction with REMOTS® sediment profile photography are an effective method for monitoring the long-term physical stability of the East Harbor OU sediment cap. Sediment grain-size and physical boundary roughness features measured in some areas of the cap, and smoothing of cap material mounds in the northern portion of the cap are evidence of the erosive

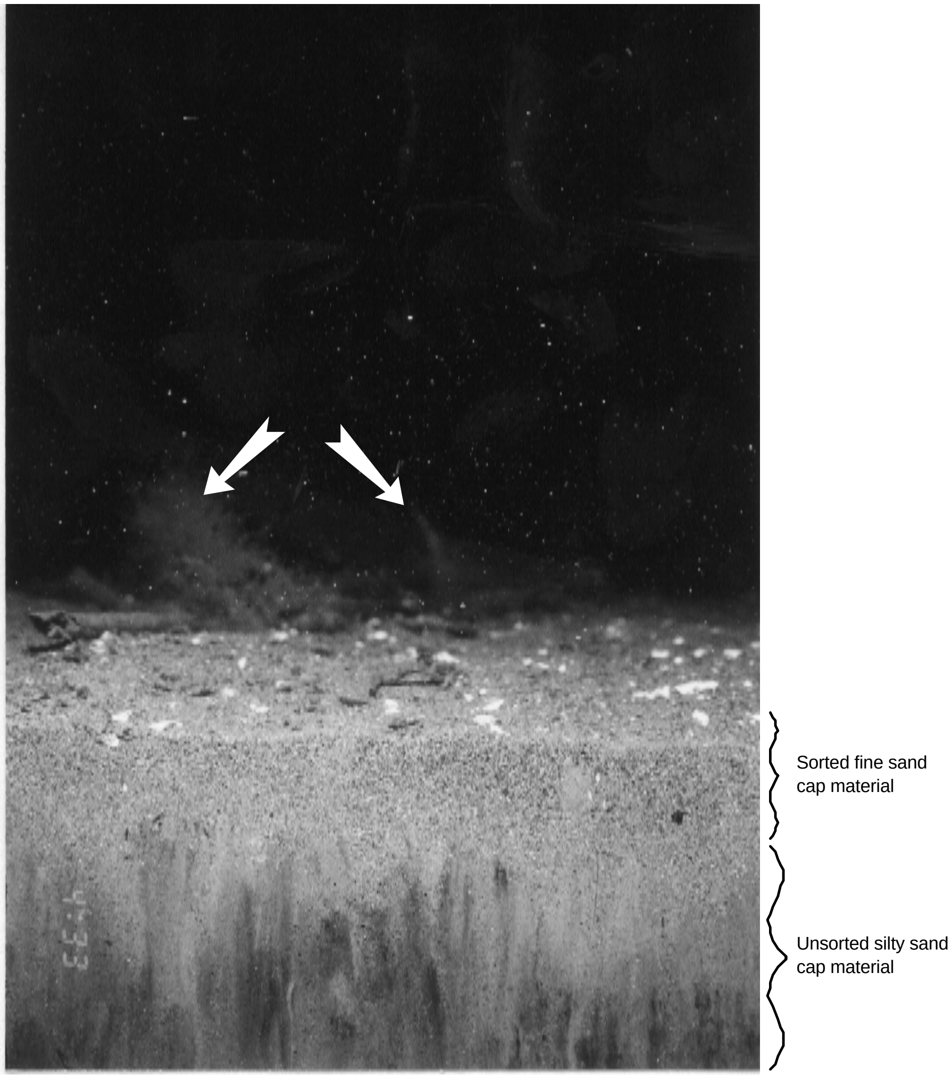

Figure 11. REMOSAE image from station T4-5 (Zone C) collected during the 1997 monitoring survey of the East Harbor. Station T4-5 is located just east of the scour zone perimeter (Zone A). Cap material is greater than prism penetration. The image shows approximately 2 cm of sorted fine sand overlying unsorted silty sand cap material. Shell, wood debris, and tubeworms (arrows) are on the surface. Image width is 15 cm.

force of ferry propeller wash. However, the repetitive bathymetric surveys conducted in Eagle Harbor suggest that significant changes in cap thickness has not occurred, with the exception of Zone A (Figure 9). Some areas surrounding Zone A have likely experienced cap erosion, but not greater than one foot (bathymetric survey threshold). It is possible that cap sediments where fine-grained sediments have been winnowed away may become armored, thus increasing cap stability in those areas. Cap areas showing physical boundary roughness features (sediment sorting, ripples, or bedforms) should be considered areas of potential cap erosion and should be closely monitored. Repetitive bathymetric surveys conducted as part of the long-term monitoring can identify cap regions where significant cap erosion is occurring.

Acknowledgments

The authors wish to acknowledge Ms. Sandy Browning and Mr. David Browning for their contributions during cap construction monitoring and post-placement monitoring of the East Harbor cap. The authors also wish to acknowledge the services of Mr. Charlie Eaton and the *R/V Kittiwake*, and the late Mr. Ted Huntley and the *R/V Discovery*.

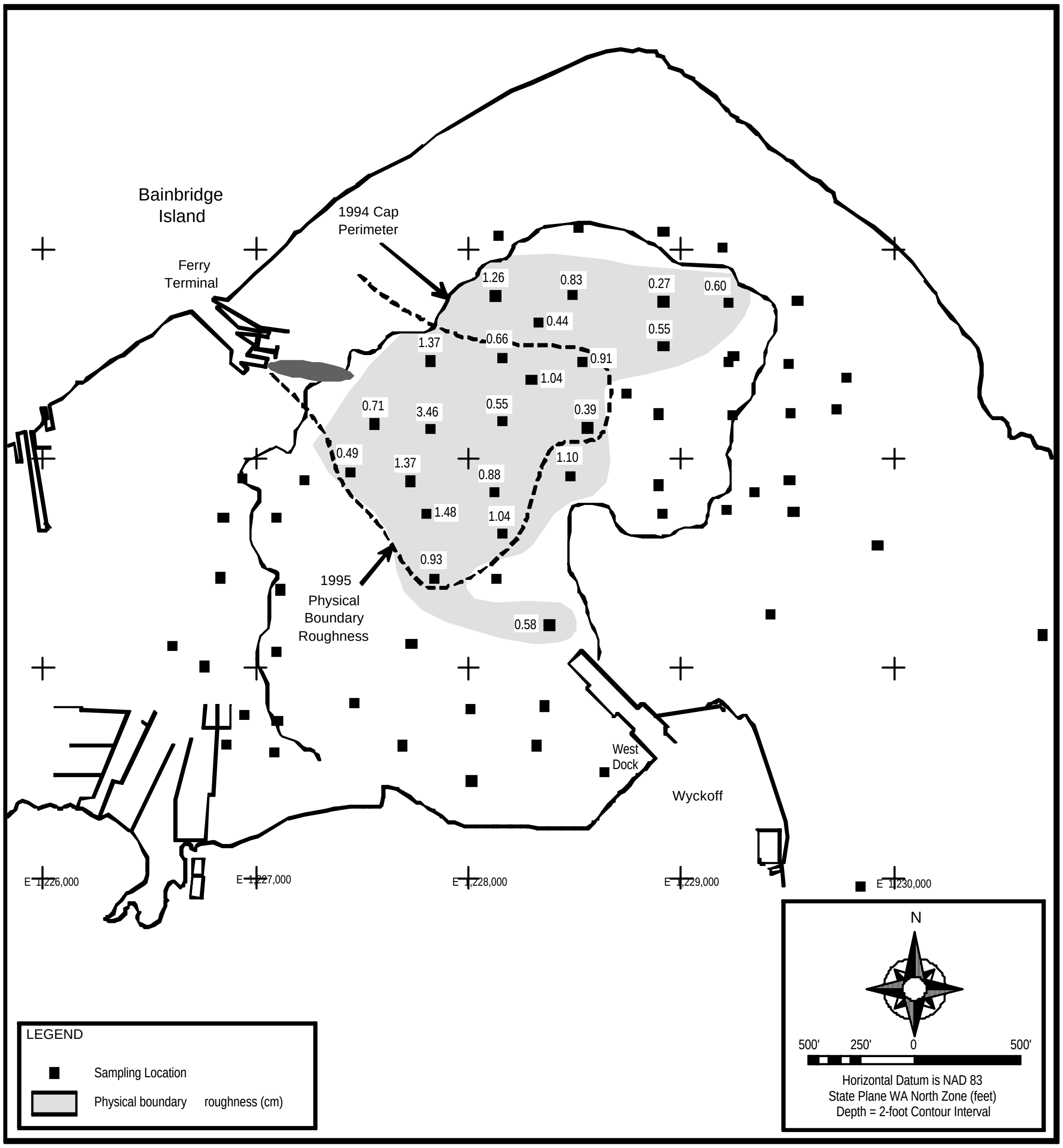

Figure 12. Physical boundary roughness attributed to sediment resuspension and transport based on the 1997 REMOSAE data.

Evidence of sediment cap colonization by benthic organisms provides a general indication of whether the cap is providing clean, suitable habitat. Organism-sediment index (OSI) values calculated from on-cap REMOTS® images suggest that cap sediments are providing suitable habitat for benthic infauna. Redox potential discontinuity (RPD) depths, which indicate the depth of biological activity, have increased since cap placement. Stage III infauna, whose presence indicate ongoing ecological succession, continue to colonize most regions of the cap.

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